

Experiments: The Operational Amplifier

I. Objective

The purpose of these experiments is to introduce the most important of all analog building blocks, the *operational amplifier* (“op-amp” for short). This handout gives an introduction to these amplifiers and a smattering of the various configurations that they can be used in. Apart from their most common use as amplifiers (both inverting and non-inverting), they also find applications as buffers (load isolators), adders & subtractors, integrators, logarithmic amplifiers, impedance converters, filters (low-pass, high-pass, band-pass, band-reject or notch), and differential amplifiers. So let’s get set for a fun-filled adventure with op-amps!

II. Introduction: Amplifier Circuit

Before jumping into op-amps, let’s first go over some amplifier fundamentals. An amplifier has an *input port* and an *output port*. (A port consists of two terminals, one of which is usually connected to the ground node.) In a linear amplifier, the *output signal* = $A \times \text{input signal}$, where A is the *amplification factor* or “*gain*.” Depending on the nature of the input and output signals, we can have four types of amplifier gain: voltage gain (voltage out / voltage in), current gain (current out / current in), transresistance (voltage out / current in) and transconductance (current out / voltage in). Since most op-amps are voltage/voltage amplifiers, we will limit the discussion here to this type of amplifier. The circuit model of an amplifier is shown in Figure 1 (center dashed box, with an input port and an output port). The input port plays a passive role, producing no voltage of its own, and is modelled by a resistive element R_i called the *input resistance*. The output port is modeled by a dependent voltage source AV_i in series with the *output resistance* R_o , where V_i is the potential difference between the input port terminals. Figure 1 shows a complete amplifier circuit, which consists of an input voltage source V_s in series with the source resistance R_s , and an output “load” resistance R_L . From this figure, it can be seen that we have voltage-divider circuits at both the input port and the output port of the amplifier. This requires us to re-calculate V_i and V_o whenever a different source and/or load is used:

$$V_i = \left(\frac{R_i}{R_s + R_i} \right) V_s \quad (1)$$

$$V_o = \left(\frac{R_L}{R_o + R_L} \right) AV_i \quad (2)$$

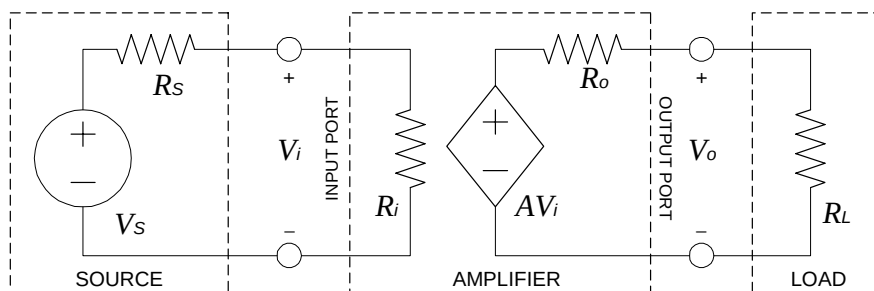


Figure 1: Circuit model of an amplifier circuit.

III. The Operational Amplifier: Ideal Op-Amp Model

The amplifier model shown in Figure 1 is redrawn in Figure 2 showing the standard op-amp notation. An op-amp is a “differential to single-ended” amplifier, *i.e.* it amplifies the voltage difference $V_p - V_n = V_i$ at the input port and produces a voltage V_o at the output port that is referenced to the ground node of the circuit in which the op-amp is used.

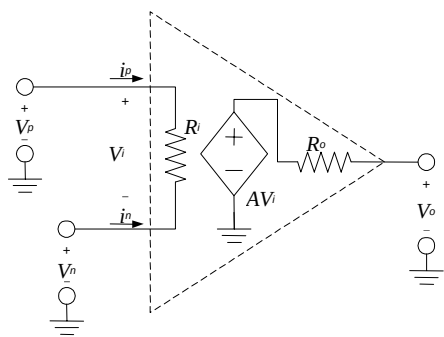


Figure 2: Standard op-amp

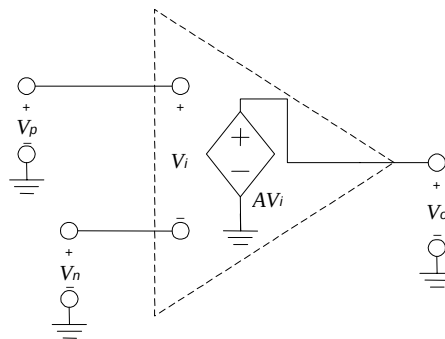


Figure 3: Ideal op-amp

The ideal op-amp model was derived to simplify circuit analysis and is commonly used by engineers for first-order approximation calculations. The ideal model makes three simplifying assumptions:

$$\text{Gain is infinite: } A = \infty \quad (3)$$

$$\text{Input resistance is infinite: } R_i = \infty \quad (4)$$

$$\text{Output resistance is zero: } R_o = 0 \quad (5)$$

Applying these assumptions to the standard op-amp model results in the ideal op-amp model shown in Figure 3. Because $R_i = \infty$ and the voltage difference $V_p - V_n = V_i$ at the input port is finite, the input currents are zero for an ideal op-amp:

$$i_n = i_p = 0 \quad (6)$$

Hence there is no loading effect at the input port of an ideal op-amp:

$$V_i = V_s \quad (7)$$

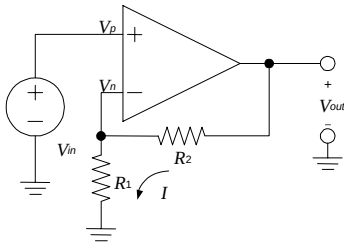
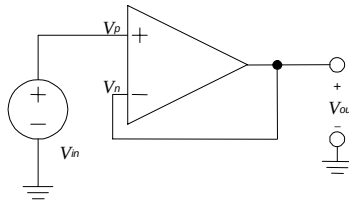
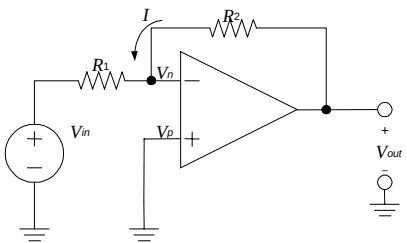
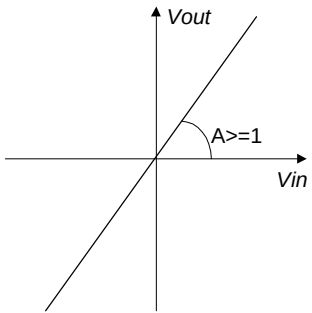
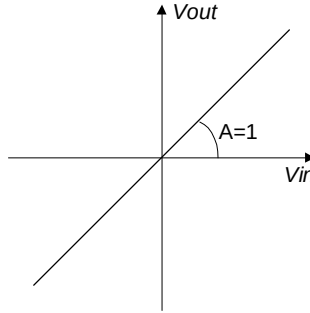
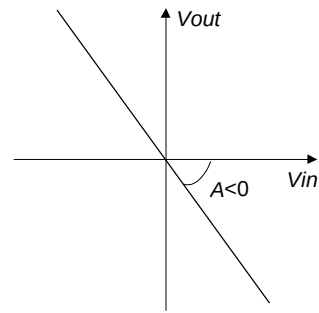
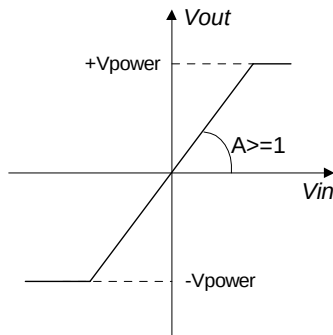
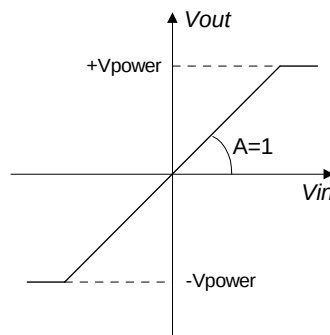
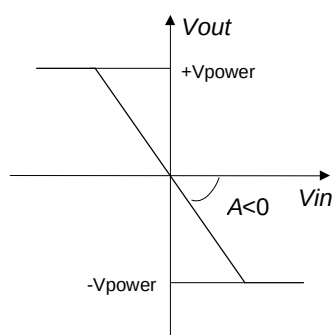
In addition, because $R_o = 0$, there is no loading effect at the output port of an ideal op-amp:

$$V_o = A \times V_i \quad (8)$$

Finally, because $A = \infty$ and V_o must be finite, $V_i = V_p - V_n = 0$, or

$$V_p = V_n \quad (9)$$

Note: Although Equations 3-5 constitute the ideal op-amp assumptions, Equations 6 and 9 are used most often in solving op-amp circuits.

**Figure 4a:** Non-inverting amplifier**Figure 5a:** Voltage follower**Figure 6a:** Inverting amplifier**Figure 4b:** Voltage transfer curve of non-inverting amplifier**Figure 5b:** Voltage transfer curve of voltage follower**Figure 6b:** Voltage transfer curve of inverting amplifier**Figure 4c:** Realistic transfer curve of non-inverting amplifier**Figure 5c:** Realistic transfer curve of voltage follower**Figure 6c:** Realistic transfer curve of inverting amplifier

IV. Non-Inverting Amplifier

An ideal op-amp by itself is not a very useful device, since any finite non-zero input signal would result in infinite output. (For a real op-amp, the range of the output signal is limited by the positive and negative power-supply voltages.) However, by connecting external components to the ideal op-amp, we can construct useful amplifier circuits.

Figure 4a shows a basic op-amp circuit, the non-inverting amplifier. The triangular block symbol is used to represent an ideal op-amp. The input terminal marked with a “+” (corresponding to V_p) is called the *non-inverting input*; the input terminal marked with a “-” (corresponding to V_n) is called the *inverting input*.

To understand how the non-inverting amplifier circuit works, we need to derive a relationship between the input voltage V_{in} and the output voltage V_{out} . For an ideal op-amp, there is no loading effect at the input, so

$$V_p = V_i \quad (10)$$

Since the current flowing into the inverting input of an ideal op-amp is zero, the current flowing through R_1 is equal to the current flowing through R_2 (by Kirchhoff's Current Law -- which states that the algebraic sum of currents flowing into a node is zero -- to the inverting input node). We can therefore apply the voltage-divider formula find V_n :

$$V_n = \left(\frac{R_1}{R_1 + R_2} \right) V_{out} \quad (11)$$

From Equation 9, we know that $V_{in} = V_p = V_n$, so

$$V_{out} = \left(1 + \frac{R_2}{R_1} \right) V_{in} \quad (12)$$

The voltage transfer curve (V_{out} vs. V_{in}) for a non-inverting amplifier is shown in Figure 4b. Notice that the gain (V_{out} / V_{in}) is always greater than or equal to one.

The special op-amp circuit configuration shown in Figure 5a has a gain of 1, and is called a “voltage follower.” This can be derived from the non-inverting amplifier by letting $R_1 = \infty$ and $R_2 = 0$ in Equation 12. The voltage transfer curve is shown in Figure 5b. A frequently asked question is why the voltage follower is useful, since it just copies input signal to the output. The reason is that it isolates the signal source and the load. We know that a signal source usually has an internal series resistance (R_s in Figure 1, for example). When it is directly connected to a load, especially a heavy (small-resistance) load, the output voltage across the load will degrade (according to the voltage-divider formula). With a voltage-follower circuit placed between the source and the load, the signal source sees a light (high-resistance) load -- the input resistance of the op-amp. At the same time, the load is driven by a powerful driving source -- the output of the op-amp.

V. Inverting Amplifier

Figure 6a shows another useful basic op-amp circuit, the inverting amplifier. It is similar to the non-inverting circuit shown in Figure 4a except that the input signal is applied to the inverting terminal via R_1 and the non-inverting terminal is grounded. Let's derive a relationship between the input voltage V_{in} and the output voltage V_{out} . First, since $V_n = V_p$ and V_p is grounded, $V_n = 0$. Since the current flowing into the inverting input of an ideal op-amp is zero, the current flowing through R_1 must be equal in magnitude and opposite in direction to the current flowing through R_2 (by Kirchhoff's Current Law):

$$\frac{V_{in} - V_n}{R_1} = \frac{V_{out} - V_n}{R_2} \quad (13)$$

Since $V_n = 0$, we have:

$$V_{out} = \left(-\frac{R_2}{R_1} \right) V_{in} \quad (14)$$

The gain of inverting amplifier is always negative, as shown in Figure 6b.

VI. Operation Circuit

Figure 7 shows an operation circuit, which combines the non-inverting and inverting amplifier. Let's derive the relationship between the input voltages and the output voltage V_{out} . We can start with the non-inverting input node. Applying Kirchhoff's Current Law, we obtain:

$$\frac{V_{B1} - V_p}{R_{B1}} + \frac{V_{B2} - V_p}{R_{B2}} + \frac{V_{B3} - V_p}{R_{B3}} = \frac{V_p}{R_B} \quad (15)$$

Applying Kirchhoff's Current Law to the inverting input node, we obtain:

$$\frac{V_{A1} - V_n}{R_{A1}} + \frac{V_{A2} - V_n}{R_{A2}} + \frac{V_{A3} - V_n}{R_{A3}} = \frac{V_n - V_{out}}{R_A} \quad (16)$$

Since $V_n = V_p$ (from Equation 9), we can combine Equations 15 and 16 to get

$$V_{out} \left(\frac{R_{A'}}{R_A} \right) = \left(\frac{V_{B1}}{R_{B1}} + \frac{V_{B2}}{R_{B2}} + \frac{V_{B3}}{R_{B3}} \right) R_{B'} - \left(\frac{V_{A1}}{R_{A1}} + \frac{V_{A2}}{R_{A2}} + \frac{V_{A3}}{R_{A3}} \right) R_{A'} \quad (17)$$

where

$$R_{A'} = \frac{1}{\frac{1}{R_A} + \frac{1}{R_{A1}} + \frac{1}{R_{A2}} + \frac{1}{R_{A3}}}$$

and

$$R_{B'} = \frac{1}{\frac{1}{R_B} + \frac{1}{R_{B1}} + \frac{1}{R_{B2}} + \frac{1}{R_{B3}}}$$

Thus this circuit adds V_{B1} , V_{B2} and V_{B3} and subtracts V_{A1} , V_{A2} and V_{A3} . Different coefficients can be applied to the input signals by adjusting the resistors. If all the resistors have the same value, then

$$V_{out} = (V_{B1} + V_{B2} + V_{B3}) - (V_{A1} + V_{A2} + V_{A3}) \quad (18)$$

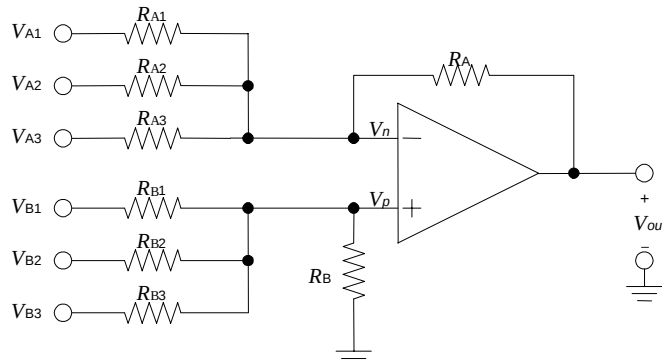


Figure 7: Operation circuit

VII. Integrator

By adding a capacitor in parallel with the feedback resistor R_2 in an inverting amplifier as shown in Figure 8, the op-amp can be used to perform integration. For example, an square wave input gives a triangular wave as output! A simple way to find V_{out} / V_{in} is to make $R_2 = \infty$. Then,

$$V_{out} = \frac{-1}{R_1 C} \int V_{in} dt \quad (19)$$

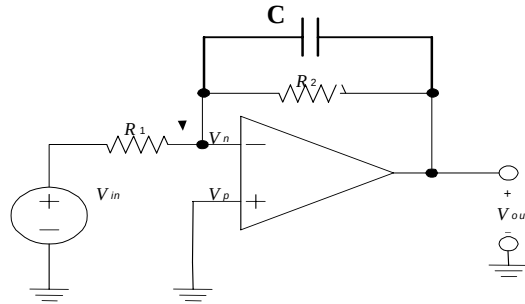


Figure 8: Integrator

VIII. Differential Amplifier

Figure 9 shows the differential amplifier circuit. As the name suggests, this op-amp configuration amplifies the difference of two input signals.

$$V_{out} = (V_+ - V_-) \frac{R_2}{R_1} \quad (20)$$

If the two input signals are the same, the output should be zero, ideally. To quantify the quality of the amplifier, the term Common Mode Rejection Ratio (CMRR) is defined. It is the ratio of the output voltage corresponding to the difference of the two input signals to the output voltage corresponding to “common part” of the two signals. A good op-amp has a high CMRR.

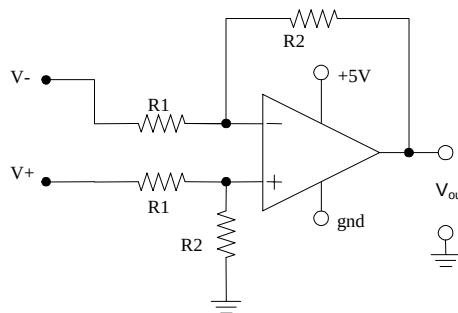


Figure 9: Differential amplifier

IX. Frequency Response of Op-Amp

The “frequency response” of any circuit is the graph of the magnitude of the gain in decibels (dB) as a function of the frequency of the input signal. The decibel is a common unit of measurement for the relative loudness of a sound or, in electronics, for the relative difference between two power levels. (A decibel is one-tenth of a “Bel”, a seldom-used unit named for Alexander Graham Bell, inventor of the telephone.) The gain expressed in dB is $20 \log_{10}|G|$. The frequency response of an op-amp is a low pass characteristic (passing low-frequency signals, attenuating high-frequency signals) as shown in Figure 10.

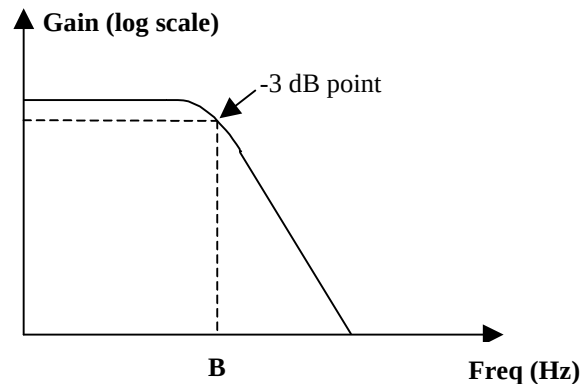


Figure 10: Frequency response of op-amp.

The bandwidth is the frequency at which the power of the output signal is reduced to half that of the maximum output power. This occurs when the gain drops by 3 dB. In Figure 10, the bandwidth is B Hz. For all op-amps, the Gain*Bandwidth product is a constant. Hence, if the gain of an op-amp is decreased, its operational bandwidth increases proportionally. This is an important trade-off consideration in op-amp circuit design. In Sections III through VIII above, we assumed that the op-amp has infinite bandwidth.

X. More on Op-Amps

All of the above circuits have one thing in common. There exists a path from the output of the op-amp to its inverting input terminal. The negative feedback ensures that the op-amp operates in the linear region (as opposed to the saturation region, where the output voltage is “saturated” at one of the power-supply voltage levels). Amplification, addition and subtraction are linear operations. Note that any DC offset in the input signal(s) is included in these operations, unless we add a capacitor in series with the input signal(s) to block the DC component(s).

XI. The LMC6482 Operation Amplifier

The LMC6482 is a CMOS-based operational amplifier. A comparison of ideal op-amp and LMC6482 characteristics given in Table I leads to the following guidelines for usage:

- One positive power-supply voltage must be connected to the LMC6482. The input voltage should fall within the range between ground and the power-supply voltage.
- The power-supply voltages limit the output voltage swing. The voltage-transfer characteristics of the non-inverting amplifier, the voltage follower and the inverting amplifier are illustrated in Figures 4c, 5b and 5c, respectively. The output swing also depends on the load resistor R_L . In order for the LMC6482 to work like an ideal op-amp, don't connect too

heavy a load (resistor of low resistance) to it. As shown in Table I, the maximum current it can output is about 30 mA. Avoid continuous operation under maximum current output; otherwise it can burn your finger!

You can refer to electronic handbooks for more detailed performance parameters of LMC6482.

Table I Comparison of ideal op-amp and LMC6482

Parameter	Ideal OP-AMP	LMC6482
Gain	∞	3,200,000
R_{in}	∞	$\sim \infty$
I_{in}	0	20fA
V_{in} Range	No limit	0V to 5V (Power supply = +5V)
V_{out} Swing	No limit	0.02V to +4.88V (100k Ω Load)
I_{out} max	No limit	30mA
Bandwidth	∞	1.5MHz
Power supply max	No Limit	+15V

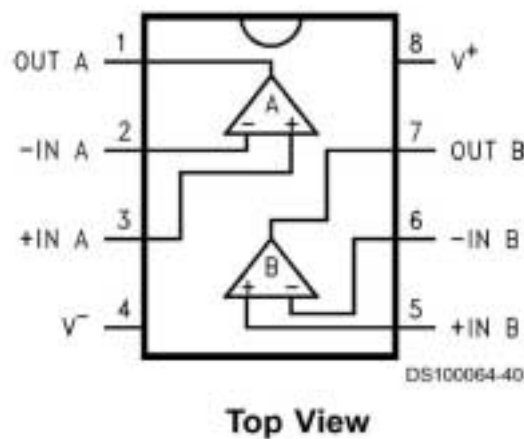


Figure 11: Pinout diagram for the LMC6482

LMC6482 pins:

The op-amp is packaged in an epoxy mini-DIP (“dual inline package”) which has 4 pins emerging from each of the two sides of the package. The most important part of the identification is to note that Pin 1 is marked by a small circular indentation in the lower left-hand corner of the package when viewed from the top side with the manufacturer’s marking reading upright. The pin numbers on ICs always start with Pin 1 being this labeled pin and increase counter-clockwise as read from the top side of the package. Thus on this particular package, Pin 8 is directly across from Pin 1, and Pin 5 is diagonally across from Pin 1. The V^+ pin should be connected to the positive power supply (+5V) and the V^- pin should be connected to ground.

Additional Information for the Operational Amplifier Experiment

I. Operational Amplifier as a Comparator

We shall look at an op-amp configuration that does not use feedback: the comparator. The purpose of the comparator is to compare two voltages and produce a signal that indicates which voltage is greater. Figure 1 below shows an op-amp as a comparator.

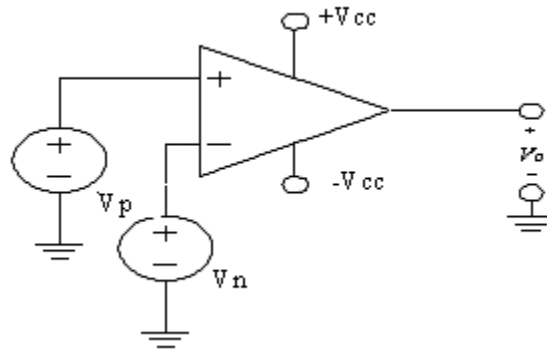


Figure 1

The principle of the comparator is based in $V_o = A(V_p - V_n)$. Since the gain, A , of an op-amp is very large, any difference will be magnified to the power supply rails $\pm V_{cc}$. If V_1 is greater than V_2 , then the difference $(V_p - V_n)$ will be positive; hence the result will be amplified to $+V_{cc}$. If, however, V_2 is greater, then the difference is negative and the result will be amplified to $-V_{cc}$. Finally, if the two voltages are *exactly* equal, then the difference will be zero and the output will also be zero.

II. Definition of Duty Cycle

Duty cycle is the proportion of time during which a component, device, or signal is operated. The duty cycle can be expressed as a ratio or as a percentage. Suppose a square wave is $+V_{cc}$ for 1 second, then is Gnd for 99 seconds, then is $+V_{cc}$ for 1 second again, and so on. The signal runs for one out of 100 seconds, or 1/100 of the time, and its duty cycle is therefore 1/100, or 1 percent.